Mirror, mirror on the wall, Which is the fairest plasma of them all?

A tale of Baseball II, 2XII and IMP

by Dietrick E. Thomsen

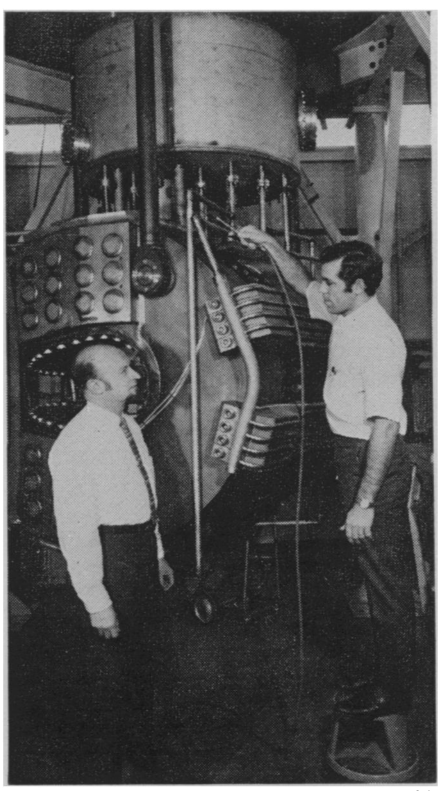
There are many ways to climb the same mountain, says the old proverb, and if the mountain is controlled nuclear fusion (CTR), plasma physicists would tend to agree. They are pursuing various approaches in the hope that one or more will work. Devices of the type called magnetic mirrors represent one of the lines of approach. At the present time in the United States three new magnetic mirror devices are beginning experiments. Their designers hope they will approach nearer to the goal, building on the significant achievements of their predecessors.

Magnetic mirrors have a natural analogue in the Van Allen radiation belts that surround the earth. Ions and electrons trapped by the earth's magnetic field are constrained to move in helical paths corkscrewing around and along the field lines. As they approach the poles, where the field strength increases, they are reflected back. The stability of particle confinement in the Van Allen belts is quite high: Some of the particles injected into them by a nuclear bomb explosion in 1958 are still there. This is heartening to plasma physicists because it shows that in principle a magnetic-mirror situation can be stable.

The Van Allen belts are characterized by very low particle densities and very long flight paths between reflections. When the physicists tried to scale a mirror machine to laboratory dimensions and make it hold a plasma of reasonable density for CTR they encountered serious difficulties. In the 20 years since the work began a significant number of the problems have been overcome, and the work is now at the point where R. F. Post of the Lawrence Livermore Laboratory could tell the Joint Congressional Committee on Atomic Energy in November that given enough support a mirror device that produced more energy than it consumed might be demonstrated by the early 1980's.

The problems arise basically because the plasma particles can set up by their own motions electrical or magnetic fields that counteract the confinement effort of the imposed field. The first and grossest to be encountered by laboratory mirror machines was the so-called hydromagnetic instability by which the plasma moves en masse across the confining field and goes to the wall of the chamber.

In 1961 the Soviet physicist A. F. Ioffe showed that the hydromagnetic instability could be overcome by adding magnet coils in such a way that the plasma trapped between the mirrors lay at a minimum point of field strength with respect to both ends and sides, thus adding a magnetic well to the magnetic mirror. Since then the magnetic well idea has been generally incorporated into mirror experiments.



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Baseball II magnet, Damm, Henning.

Some time later Post and collaborators at Livermore found that a coil shaped like the seam on a baseball would also produce a magnetic well. A group led by Charles Damm is beginning a second baseball experiment, using a superconducting magnet designed by Carl Henning.

After taking care of the hydromagnetic instability, physicists turned their attention to the microinstabilities. These involve various kinds of disturbance in small regions of the plasma that may grow until they become disruptive. For example, energy may be exchanged between plasma particles and electromagnetic waves in the plasma in a resonant way so that a vibration grows until it becomes destructive.

Work in recent years has identified several microinstability modes, and, when the conditions required by theory are met, they can be suppressed. Other modes predicted by theory have not yet been seen, and one of the purposes of the three new experiments is to see whether they appear as plasma density and temperature approach closer to controlled fusion conditions than the past generation of devices. "The road is a hard one," says Post, "but seemingly a clearly marked one: Sufficient care in the preparation of the plasma and in the shaping of its confining fields should result in a plasma stability adequate for good confinement."

The three new experiments, Baseball II and 2XII at Livermore and IMP (Injected Microwave-heated Plasma) at Oak Ridge National Laboratory, are also designed to work on various aspects of particle injection and loss and energy cycles in mirror machines.

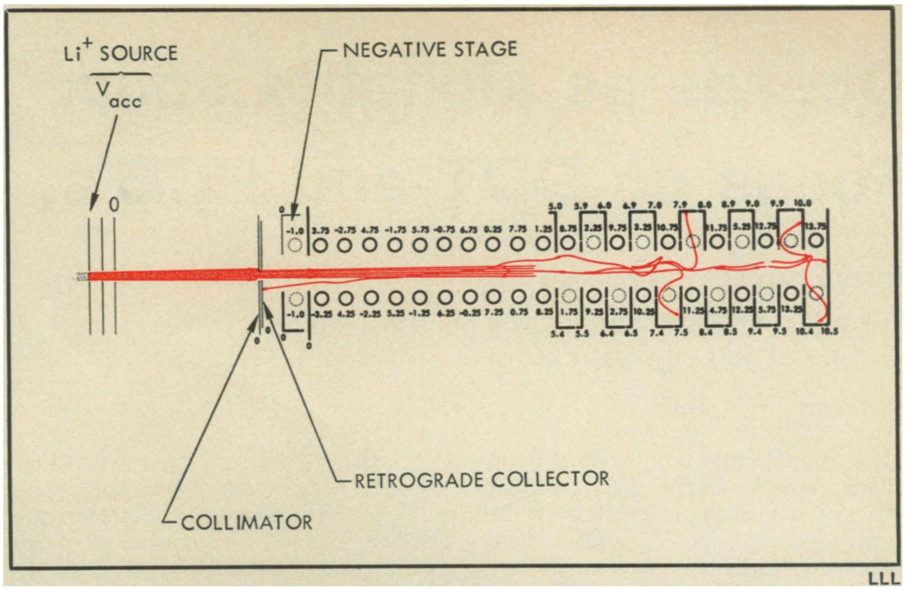
Even when all instabilities are surpressed there will be a high rate of loss of plasma particles through the mirrors. At these densities there are collisions between particles, and the collisions can knock particles through the mirror. To offset the loss new particles need to be continually injected. Also the departing particles carry energy away with them, and for efficient operation this energy must somehow be recovered and returned to the beginning of the cycle.

Post envisions a mirror machine system similar to a gas turbine. In a gas turbine the turbine shaft drives a compressor that pumps air across the nozzles where fuel is burned. The hot gas produced in the fires turns the turbine shaft. If the thing is engineered right, the gas will give the turbine shaft a little more energy than the compressor needs and this is raked off for use elsewhere. In a fusion mirror machine, the energy carried by escaping particles would be recovered and used to inject new particles. The energy produced by the fusions that went on would provide the rake-off and compensate for the inefficiency of the recovery.

When particles are injected into a mirror machine they have to be electrically neutral to get through the magnetic field into the plasma region; the field would bounce them back if they were charged. To get a beam of neutral particles headed toward the plasma at some speed, experimenters start by accelerating beams of ions. (Neutral particles cannot be accelerated.) When the ions are all in a beam moving speedily in the right direction they are passed through neutral gas from which they take electrons and neutralize themselves. The moving, now neutral, beam then crosses the field into the plasma. The plasma then has to ionize and heat it.

One way to do this efficiently is to provide a very hot target plasma for the incoming neutral beam to strike. The IMP experiment at Oak Ridge will study ways of making such a target plasma by heating the electrons with microwaves in a manner similar to a microwave cooker. IMP will also attempt to find out how high the pressure of the plasma against the magnetic field can be while the plasma still remains trapped in the mirror. Experiments that preceded IMP have shown that in cases where the outward plasma pressure was nearly equal to the inward field pressure (the majority of CTR experiments operate at much lower plasma pressure) the plasma was not only free of instabilities but also aided its own confinement. In Post's words "the electrons were capable of digging their own magnetic well and then sitting quite happily in it."

Livermore's 2XII is intended particularly to study the decay of a quiescent plasma—one without instabilities—transiently confined in a magnetic mirror. According to Post the confinement time of a magnetic mirror cannot be increased by making the device larger as can be done with toroidal devices. Better confinement depends on improving the behavior of the quiescent plasma. (This situation also has an advantage: Because size doesn't matter nearly as much, it would be possible in principle to make much smaller fusion reactors out of mirror machines than from toroids.)



Direct conversion of charged-particle motion to electric current.

Baseball II will also study neutral beam injection. If the neutral beam has a high kinetic energy when it is injected, it will automatically become a hot plasma when it is ionized by plasma already in the trap. Experiments are planned to study the characteristics of plasmas that can be built up by this "bootstrap" trapping, as Post calls it.

To recover the energy of particles that escape, Post and collaborators are developing a device that will directly convert the motion of the escaping particles to an electric current. The particles come out of the plasma with motion in random directions. First they are put through a magnetic field arrangement similar to a nozzle that brings them all to motion in the same direction. Then the particles go through a small magnetic field that bends away the electrons and deposits them on an electrode that serves as negative terminal for the current driver. The ions, being much heavier and having more momentum than the electrons, are less affected by the field and pass on into a chamber where a succession of electrodes sets up an electric field designed to slow them down and stop them.

The ions come out of the plasma with a random spread of energies, and so they will come to rest at different points in the retarding field. The succession of electrodes is designed to catch each ion just as it comes to zero velocity. Post says that a simpler device could be built with a single electrode calculated for an average energy, but this would mean that some ions would strike it with a residual velocity and some would never reach it. The energy associated with the excess velocities would be dissipated as heat and lost to the system. The multiple-electrode collector is more efficient.

In principle such a collector could achieve conversion efficiencies of 85 to 90 percent. Laboratory tests of a small scale model at LLL have reached 83 to 87 percent, and Soviet reports indicate 90 to 95 percent.

The converter generates a high voltage direct current which can then be returned to the injector to accelerate particles for injection. If there is any excess it can be drained into a power grid. The over-all efficiency of the whole system would be less than that of the converter, but could reach 50 or 60 percent.

If mirror reactors are built to use what physicists consider the easiest fuel cycle to achieve, deuterium fusing with tritium, the direct converter would be an auxiliary recovering energy escaping from the plasma. The energy generated by the fusions in this case is carried mainly by neutrons, which will not give it up to an electric converter. The neutrons' energy must be extracted by making them heat some substance as they pass through it. A blanket of liquid lithium is generally favored.

Other cycles are possible but more difficult to achieve. Post hopes to see a deuterium plus helium-3 cycle. In this case the fusion energy is carried away by charged particles and the direct converter could be used to recover it as well. Such a system could run at very high efficiencies.

If each of the three experiments succeeds in answering the questions it has set for itself, together they may make an advance toward using mirror machines in fusion reactors. □